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## FINAL REPORT

on

## A DESIGN STUDY OF A PHOTOREFRACTIVE PAGE COMPOSER

to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
MARSHALL SPACE FLIGHT CENTER

NASA Contract NAS8-31291

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## ABSTRACT

For the past several years, the NASA Marshall Space Flight Center has been involved in the development of a block-oriented random access holographic memory system for the storage of large quantities of digital data. A key component of this system is the block data composer or page composer. The page composer serves the dual functions of a buffer memory and optical object whose hologram is ultimately stored in the memory. This program was devoted to a laboratory demonstration and preliminary system analysis of a new type of page composer designed to have the dual advantages of low optical loss and small size.

The current page composer is optically addressed and functions by virtue of optically induced refractive index changes in the active material. Laboratory demonstrations of the device were successfully performed using  $10 \times 10$  bit and  $128 \times 128$  bit data arrays. It has been established that the only significant obstacle to the construction of a brass-board model working at megabit data rates is the lack of sensitivity of the photorefractive materials which were considered during the course of this study. Possible materials for future consideration are the photo-plastics. While they have more than the required sensitivity, their stability and suitability for double exposure holography has not been investigated. If a sufficiently sensitive material is found, then the photorefractive page composer could be built to perform in a highly efficient fashion which would result in an overall reduction of the size of the memory system and an easing of the requirements upon the sensitivity of the holographic recording material.

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## FOREWORD

This report was prepared by Battelle, Columbus Laboratories, under Contract No. NAS8-31291. The program has been monitored by George A. Bailey of the Astrionics Laboratory, NASA Marshall Space Flight Center.

The Principal Investigator for this effort is Dr. C. M. Verber of Battelle's Solid State and Optical Sciences Section. Other contributors to the work and to this report were C. E. Moeller and C. M. Chapman.

## INTRODUCTION

For the past several years, the NASA Marshall space Flight Center has been involved in the development of a block-oriented random-access memory (BORAM) optical system for the storage of large quantities of digital data. The system has been designed, studied and reduced to practice, at least in the form of a laboratory model, by The Radiation Division of Harris Intertype. A schematic of the system is presented<sup>(1)</sup> in Figure 1.

The BORAM system is a holographic system which accepts a stream of digital data, via an appropriate interface, at the Block Data Composer (Figure 1) or "page composer". This device stores the incoming data in an optically accessible form. To complete the storage cycle, a hologram is made of the optical bit pattern on the page composer. The page composer is then erased so that it can receive a new block of data. The memory is read by reconstructing the hologram of the page composer on a suitable detector array. In the ideal BORAM system, the page composer should have a  $128 \times 128$  bit capacity and should operate at megabit rates.

The goal of the present program has been to demonstrate the feasibility of a novel page composer concept which should result in a page composer which is significantly smaller and suffers from fewer optical losses than do previously suggested versions of this device. The page composer, which will be described in detail below, is optically addressed and functions as a result of a change in the index of refraction of the page composer medium induced by the addressing beam. Hence, the name "photorefractive page composer" (PRPC) for this device.

A laboratory demonstration of the PRPC has been successfully carried out. In addition, calculations and design studies have been performed which indicate that, with the incorporation of a suitable photorefractive material, the PRPC can indeed solve many of the current page composer problems.

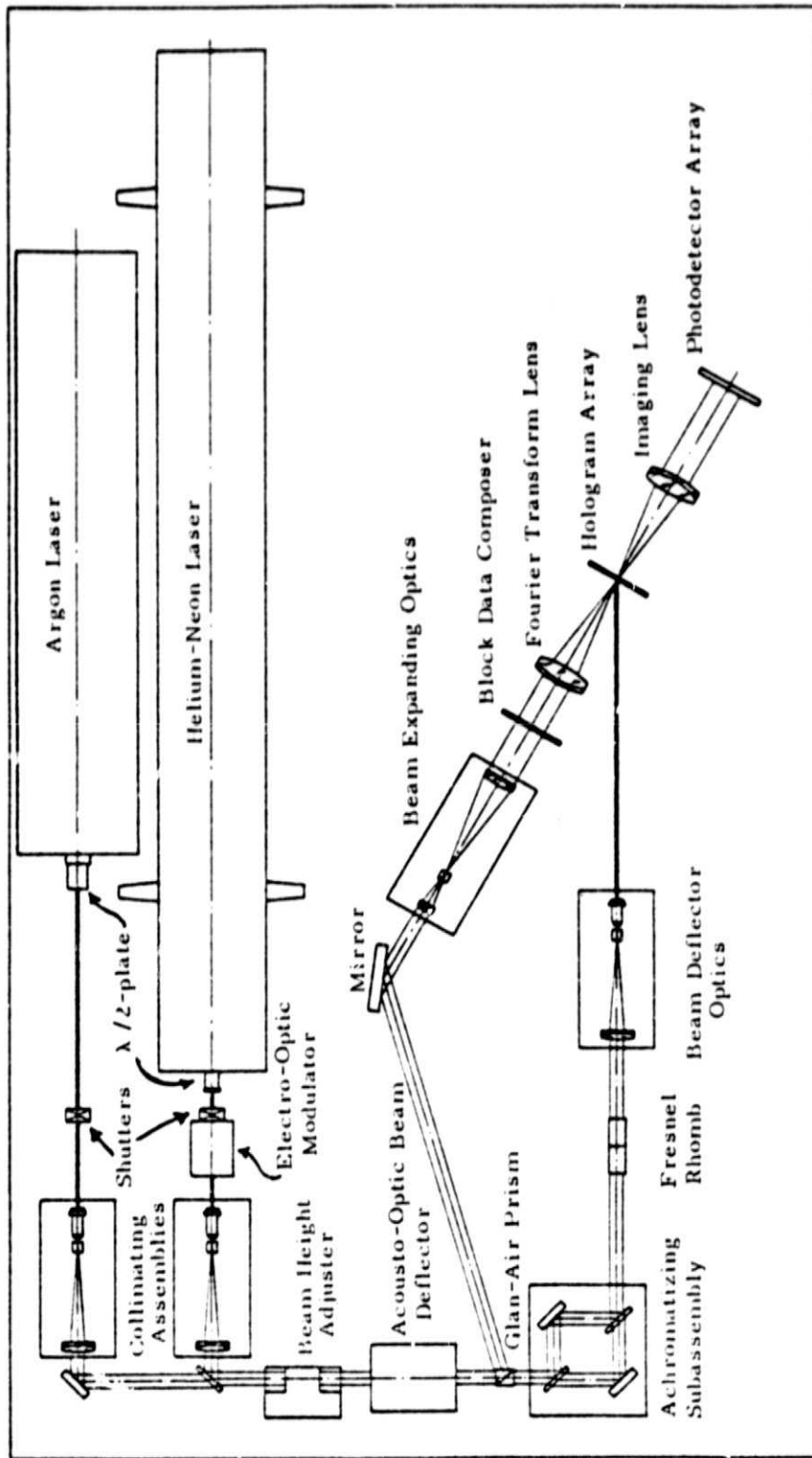


FIGURE 1. SCHEMATIC OF BLOCK ORIENTED RANDOM ACCESS MEMORY SYSTEM (1)

## TECHNICAL BACKGROUND

As a background to the body of this report, which will be concerned primarily with a description of the laboratory feasibility studies of the photorefractive page composer and the system considerations which will impact on its ultimate design, this section will deal successively with;

- The Function and Desired Characteristics of the Page Composer
- The PRPC Concept.

### THE FUNCTION AND DESIRED CHARACTERISTICS OF THE PAGE COMPOSER

In the BORAM system the page composer (PC) must perform two essential functions. First, as the data stream enters the memory system it is stored in the PC in a predetermined geometric array. In its capacity as a buffer memory, the PC must be able to store over  $10^4$  bits. To allow enough time for subsequent steps in the overall operation of the memory, the PC must be able to accept data at about twice the data rate of the entire system. Acceptance rates of greater than  $10^6$  bits/sec are therefore required. Since, in normal operation, the PC is read only once, it can be a volatile memory. Additionally, since, at maximum data rates, it will be cycled every  $10^{-2}$  sec, it need not have a very long storage time. Of course, if the intrinsic storage time of the PC is only several hundredths of a second, some provision would have to be made for handling very low data rates.

The second function of the PC is that of serving as the object whose hologram is recorded in the memory plane. This function imposes a number of optical requirements on the PC, as enumerated below.

Size. Since the diameter of the page composer plays a large part in determining the dimensions of the entire optical system, it is desirable to make the page composer about the size of the detector array. As will be shown below a  $10^4$  bit PRPC can be smaller than  $1 \text{ cm}^2$ . This allows an exceedingly compact optical system, but does limit the number

of  $1 \text{ mm}^2$  hologram sites on the memory plan which can be addressed without moving any of the optical components. Allowing translational motion of the memory plane would, of course, remove this difficulty.

Contrast ratio. As the BORAM system is read by reconstructing the hologram of the page composer on a detector array, the contrast ratio of the reconstruction is one of the principal determining factors in the signal-to-noise ratio, and therefore in the bit error rate of the entire memory system. The PRPC can easily provide contrast ratios well in excess of 100:1.

Optical Thruput. The signal beam which is used to write the hologram in the memory plane must be transmitted or reflected by the page composer in order to have the appropriate digital pattern imposed upon it. Any optical loss in the page composer must therefore be compensated for by the use of a larger laser or a more sensitive memory material. The former approach is very undesirable from the overall system point of view, while the problem of obtaining sensitive, reversible recording materials still lacks a satisfactory solution. The page composer should therefore introduce minimal losses into the optical system. The PRPC manages this by using a material which is, at all times, completely transparent to the beam used to write the hologram.

Erasability. It must be possible to restore the page composer to a receptive state with a minimal use of energy or elapsed time. As will be described below, it is a feature of the PRPC that it requires only partial erasure to restore it to a receptive state.

## THE PRPC CONCEPT

### Photorefraction

The photorefractive page composer is based upon the fact that it is possible to effect a significant, reversible change in the index of refraction of some materials by irradiating them with light of an appropriate wavelength and intensity. Many such materials exist. If the optically induced change results in a color change they are called

photochromics. If the change in absorption spectrum occurs in the ultraviolet, there will still be associated index of refraction changes in the visible region even though the visible absorption spectrum remains unchanged. Materials exhibiting this effect are called photorefractive.

Another type of photorefractive material is typified by  $\text{LiNbO}_3$ .<sup>(2)</sup> Here the change in index is due to the electrooptic effect which causes optically induced changes in the electron distribution that result in index of refraction changes. Both types of photorefractive materials can be used in the PRPC.

### The Photorefractive Page Composer

The operation of the PRCP can best be understood with reference to Figure 2, which is a block diagram of a possible PRCP configuration. The first set of critical components are a pulsed laser followed by an optical gate and then a raster-scanned two-axis deflector. Along with suitable optics, this set of components forms and scans a pulsed, modulated laser beam across the next major component, the photorefractive page composer plane. The plane contains a  $128 \times 128$  array of resolvable locations, each of which receives a pulse which induces an index of refractive change  $\Delta n$  representing a digital one, or no pulse, representing a digital zero. The photorefractive plane stores this pattern of index variations until it is used as the object of the hologram formed on the memory plane by Laser 2.

As in any of the proposed holographic memory systems, the data is read out of the memory by reconstructing the hologram of the PC on a photo-detector array. In the present system, this would result in an image of a phase object which would be unintelligible to the intensity sensitive photo-detector array. Therefore, a phase reference must be introduced to transform the stored phase information into intensity information. This is most simply done by first recording a hologram of the "empty" page composer, then filling the PC with the desired series of  $0^\circ$  and  $180^\circ$  phase shifts and superimposing the hologram of this data page on that of the reference page. When played out, the result will be the interference pattern of the two holograms which will be the desired intensity pattern.

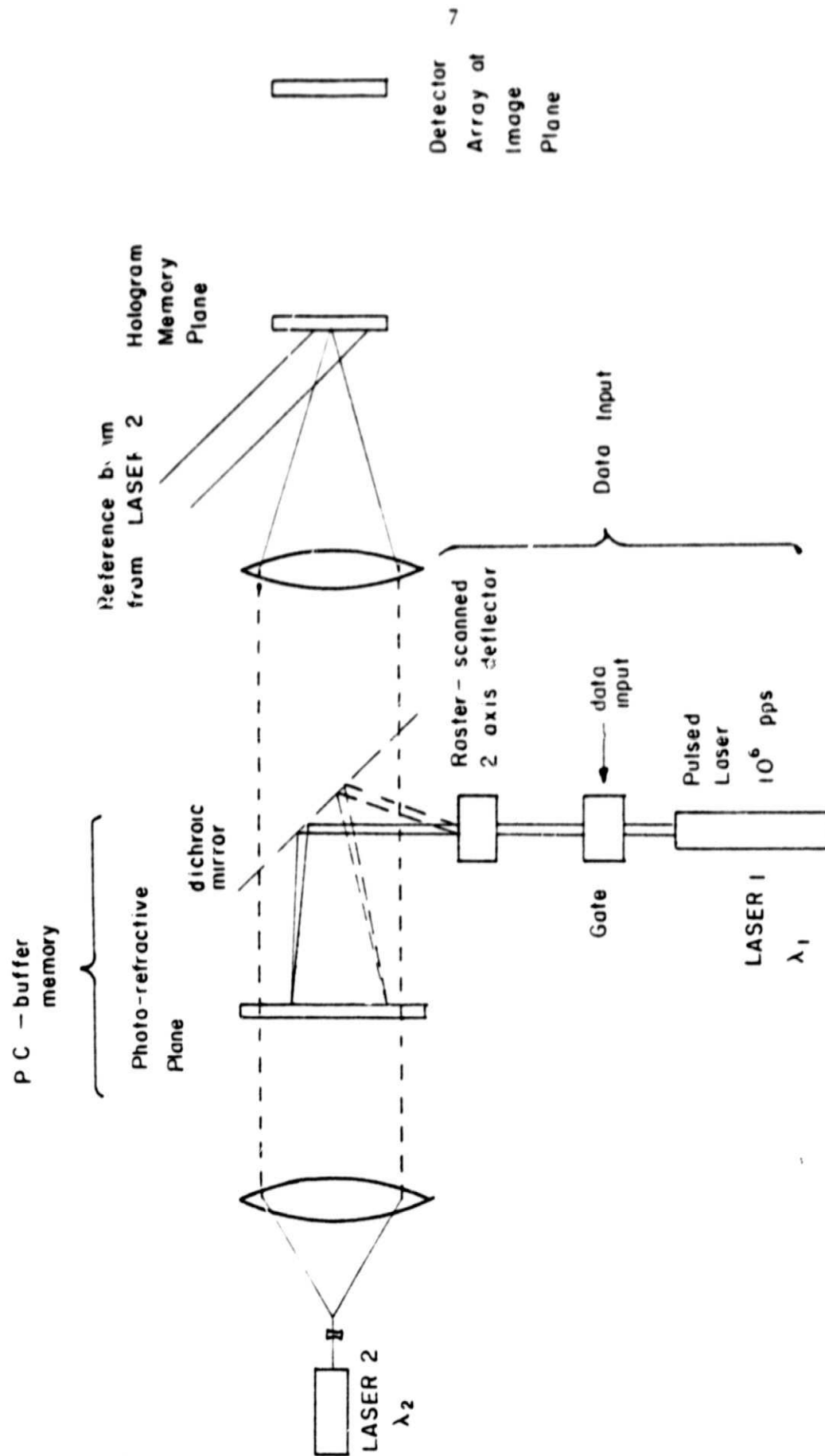


FIGURE 2. BLOCK DIAGRAM OF A POSSIBLE PRPC CONFIGURATION

The effect of introducing a  $180^\circ$  phase shift in part of the hologram-writing beam can be understood by a brief consideration of a Michelson interferometer. The Michelson interferometer produces an interference pattern by recombination of two beams of light originating from the same source as is shown in Figure 3. The bright lines of the interference pattern represent regions of constructive interference or regions where the amplitudes of the two wavefronts are in phase. If one observes a bright fringe while increasing the optical path length of one arm of the interferometer by half a wavelength, the bright fringe now becomes a dark fringe. This occurs because the increased path length delays the arrival of the wavefront such that it is now  $180^\circ$  out of phase with the wavefront from the other arm. As an alternative to increasing the path length of one arm, a thin sheet of material of refractive index,  $n_1$ , ( $n_1 \neq n_{\text{air}}$ ) and thickness,  $t$ , may be inserted into one arm. This changes the optical path length by  $(n_1 - n_{\text{air}}) t$ . If  $n_1$  and  $t$  are chosen so only a  $1/2$  wavelength path length is produced the same effects on the fringe pattern as noted above are produced. This situation is analogous to the phase change in the page composer.

In the PRPC, the light beams associated with each arm of the interferometer are replaced by the holograms of the "empty" and filled pages. Because the geometry is not changed between the two exposures, the two holograms overlap perfectly and interfere constructively, producing a single uniformly bright image of the page composer except where a slight refractive index change is induced in a small element of the page composer between holographic exposures. If  $\Delta n$  is controlled so that for part of the beam there is an effective path length change,  $\Delta n t$ , which is a half a wavelength, then the phase of the wavefront from that particular element is delayed by  $180^\circ$  for the second exposure. Since the reconstructed image of a hologram is composed of wavefronts identical to those which came from the page composer during the recording process, the two images will interfere constructively in all areas except for the elements having undergone the  $180^\circ$  phase shift. For these elements destructive interference will occur. The resulting image will be uniformly bright except for the small elements which will appear as a dark spot.

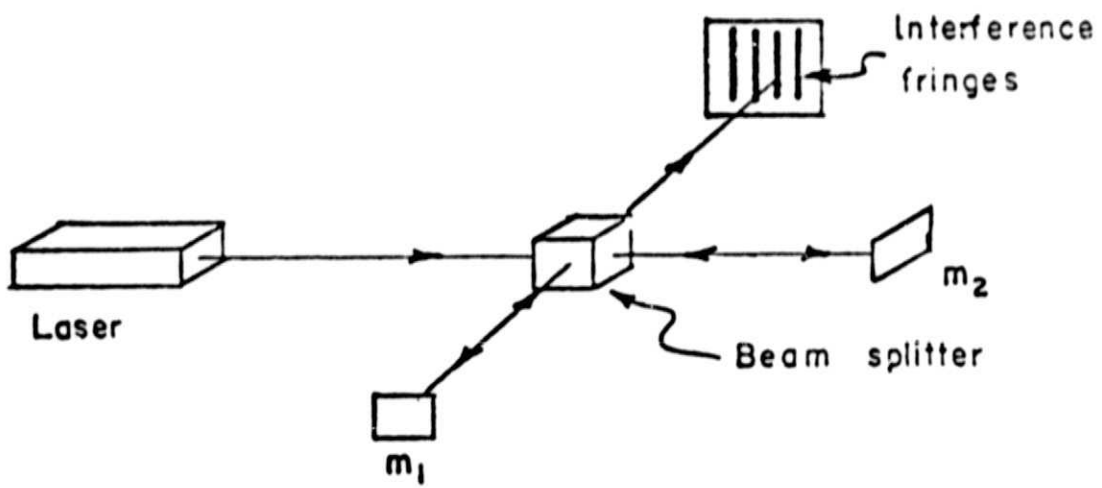


FIGURE 3. MICHELSON INTERFEROMETER SHOWING  
PARALLEL INTERFERENCE FRINGES

Because the page of data is ultimately recorded as a phase difference between a "reference page" and the data page, index variations in the reference page which are left unchanged in the data page will automatically cancel out. This means that the photorefractive plane does not have to be completely erased between pages. Moreover, material imperfections and beam inhomogenieties which are constant in time will have no effects on the information read out of the memory.

## LABORATORY DEMONSTRATION OF THE PHOTOREFRACTIVE PAGE COMPOSER

During the course of this program, experiments were performed which demonstrated the feasibility of the PRPC concept first on a  $10 \times 10$  array and then on a  $128 \times 128$  jittered array. The primary photorefractive material and was iron doped  $\text{LiNbO}_3$ .

A schematic diagram of the laboratory arrangement is shown in Figure 4. It differs in several important aspects from the arrangement shown in Figure 2. First, in order to avoid the expense of a suitable two-axis deflector, a fixed data mask was imaged on the photorefractive material to simulate the entry of a representative bit pattern. The use of a parallel data entry system to simulate the serial data entry of the actual device in no way alters the validity of the experiments since all subsequent steps occur in a time which is much less than the retention time of the photorefractive material. Second, the mirror in the reference beam was mounted on a piezoelectric translator so that a  $\pi$  phase shift could be introduced in the reference beam between the two exposures of each double exposure hologram for reasons which will be discussed below. The hologram is a pseudo-Fourier-transform hologram since the recording material (Kodak 649-F) is located 3 to 4 mm in front of the focal plane of the Fourier-transform lens. The field lens in the data beam is used to adjust the angular orientation of the light rays in the data write beam so that they are approximately parallel to the light rays in the hologram recording beam.

In most of the experimental work performed on this program, iron doped lithium niobate ( $\text{LiNbO}_3$ ) was used as the photorefractive material. Since it is sensitive to blue light, the  $4880\text{\AA}$  line of an argon-ion laser was used to write the data into the PRPC. Since  $\text{LiNbO}_3$  has a much reduced sensitivity to red light, it was convenient to use the  $6328\text{\AA}$  line of a He-Ne laser to record the holograms of the PRPC. Kodak 649-F plates were used to record the holograms.

A  $10 \times 10$  bit array of  $50\mu$  spots on  $100\mu$  centers was written, recorded and read out. The array was formed by imaging a drilled sheet-metal data mask onto the  $\text{LiNbO}_3$  crystal. Initially, the double exposures

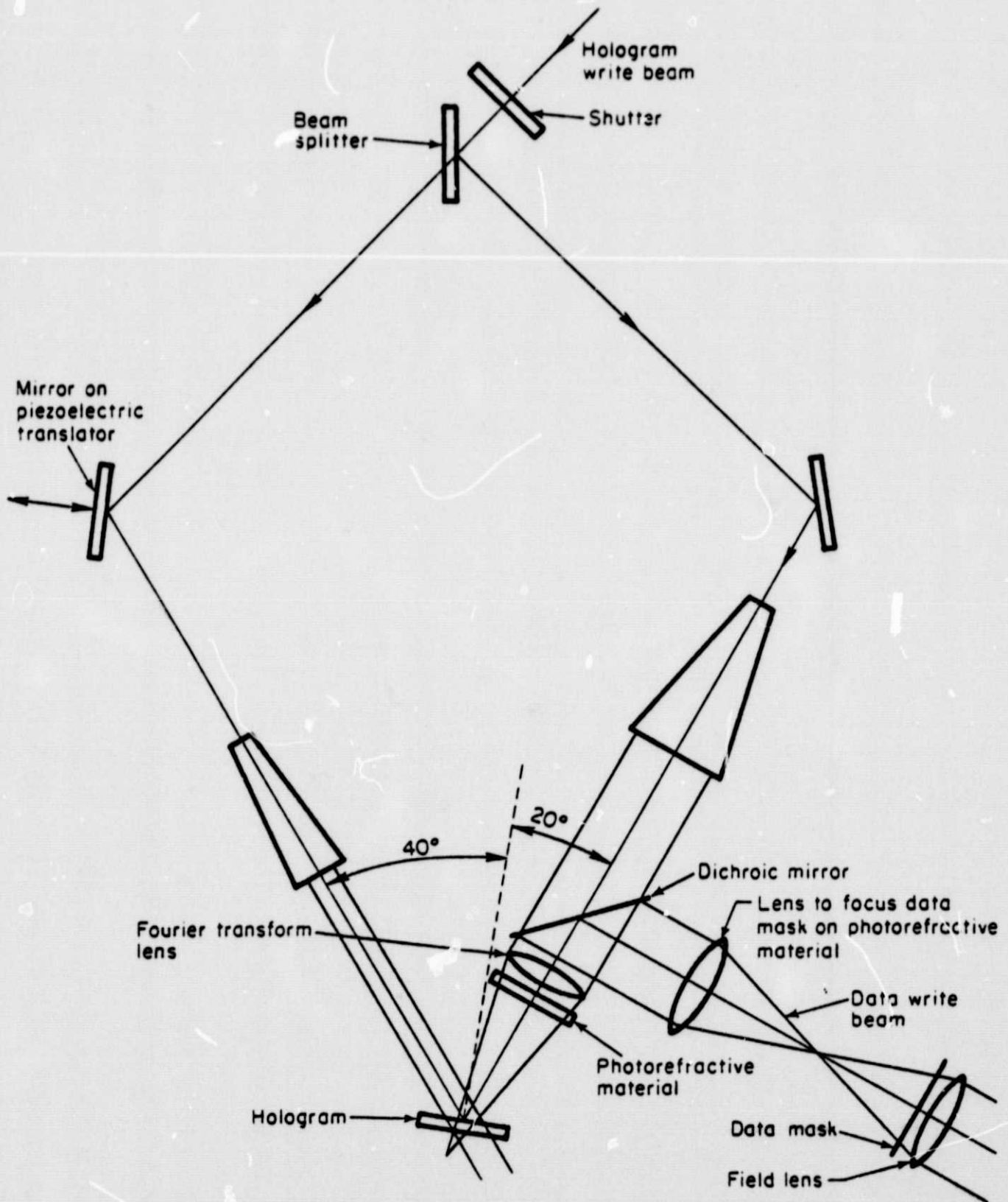


FIGURE 4. BLOCK DIAGRAM OF THE DEMONSTRATION MODEL OF THE PRPC

were made without introducing the  $\pi$  phase shift in the reference beam. The result of reconstructing the hologram was a generally unsatisfactory array of dark spots on a bright background. This situation was improved enormously by the introduction of a  $\pi$  phase shift in the reference beam between exposing the reference and the data holograms. This resulted in an array of bright spots on a dark background.

There are two advantages in using the  $\pi$  phase shift between exposures. The first is that it is easier to photograph and see a small light area on a dark background, than it is to photograph and see a small dark area on a light background. The second reason is that it is easier to introduce a controlled phase shift with a piezoelectric translator in the reference beam than it is to determine the necessary exposure of the PRPC material to obtain a  $\pi$  phase shift. As will be discussed in detail in a later section of this report, the accuracy with which a  $\pi$  radian ( $180^\circ$ ) phase shift is produced, determines the contrast ratio in the detector plane. For example an error of 0.2 radians ( $11.5^\circ$ ) in the phase shift will reduce the contrast ratio from a theoretical value of infinity to 100:1. An additional .08 radians ( $4.8^\circ$ ) reduces the contrast ratio to 50:1. The contrast ratio is also dependent upon the intensity balance between the two holograms.

Figure 5 is a photograph of the magnified real image of a double exposure hologram of the PRPC with the  $10 \times 10$  bit array written in it between the two exposures. Figure 6 is the truth table for the mask. A (\*) represents a hole in the mask. There is some nonuniformity of the dots in the array of Figure 5 because of nonuniformity in the beam illuminating the data mask.

The PRPC material had been written in several times in the general area shown in Figure 5 before the reference hologram for the displayed data array was made. There is a complete absence of the previously written data in this reconstruction, demonstrating that it is not necessary to completely erase the previous data everytime new data is to be written. Of course the old data will have to be erased eventually, since there is only a limited  $\Delta n$  available in the PRPC material.



FIGURE 5. REAL IMAGE OF A DOUBLE EXPOSURE HOLOGRAM OF  
10 x 10 BIT PATTERN ON PRPC

*	*	*	*	*		*	*		
*	*			*	*	*	*	*	*
*	*	*	*			*	*		
*			*			*			*
*		*				*		*	
*	*		*		*		*		*
		*	*	*			*	*	*
	*	*		*	*			*	*
			*	*	*			*	*
*					*		*		*

FIGURE 6. TRUTH TABLE FOR 10 x 10 DATA MASK  
 (\* INDICATES A HOLE IN THE MASK)

The experimental arrangement shown in Figure 4 was also used to record and play back an  $128 \times 128$  data array. The bit locations on this mask are slightly displaced (in a quasi-random fashion) from their ideal location, thus placing a higher strain on the system resolution. The data mask was projected on the PRPC so that it formed an image of about  $1.3 \times 1.3$  cm, giving an approximate  $100 \mu\text{m}$  center-to-center dot spacing. A magnified image of the play back of the recorded data array is shown in Figure 7. The nonuniformity of the contrast ratio across the data array is caused by the lack of stability of the holographic apparatus over the long (10 min.) time period between the two hologram exposures which elapses while the data is written in the PRPC. This should not be a problem in a working system where the time between the two hologram exposures should be on the order of 10 msec. It should also be pointed out that the current system was designed for laboratory demonstration purposes only and does not have the thermal stability expected in a well designed brass-board device.

The long data writing time required in this demonstration is due in part to the insensitivity of the iron doped  $\text{LiNbO}_3$ , but the primary cause is that the data are entered by the flood illumination of a mask which is very inefficient, but inexpensive way to simulate data entry into the PRPC. Some of the data points are missing in one of the corners of the array because they were cut off by the dichroic mirror mount. A truth table for the  $128 \times 128$  data array is shown in Figure 8.

Attempts were made to use various cis-trans materials as the photorefractive element. However, as discussed below, their sensitivities were found to be so low that prohibitively long exposure times were required.

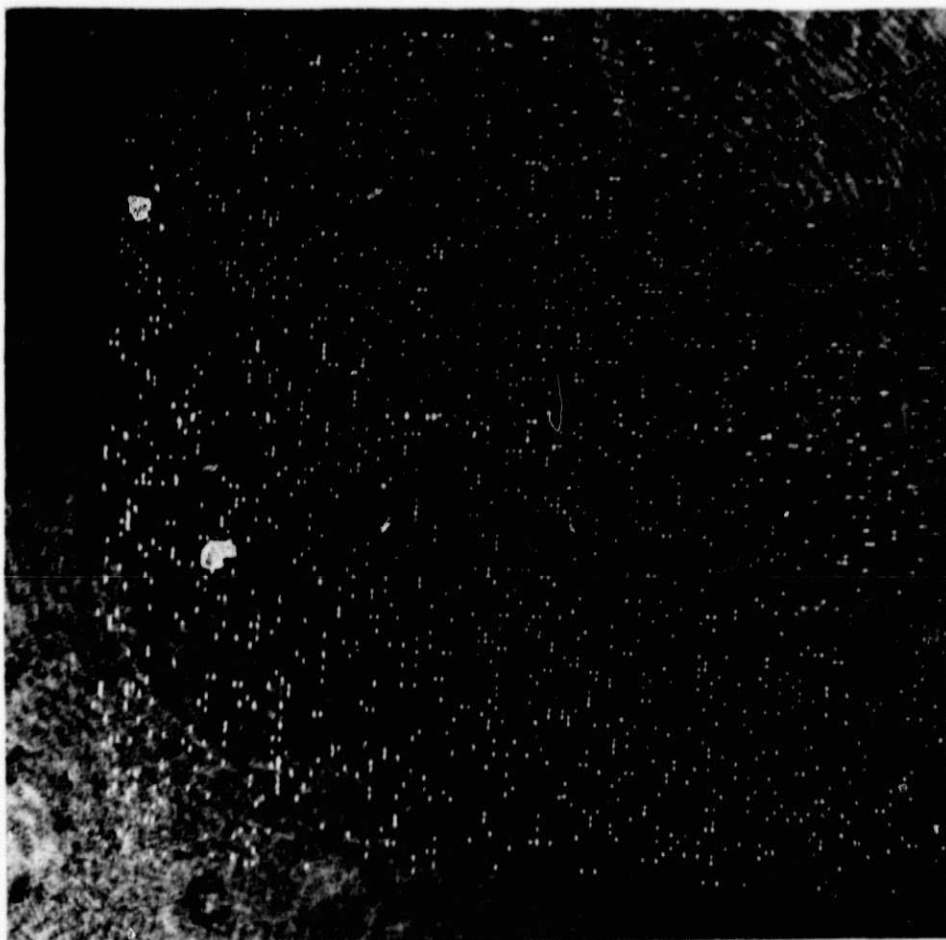


FIGURE 7. RECONSTRUCTION OF DOUBLE EXPOSURE HOLOGRAM OF  
128 x 128 BIT JITTERED MASK

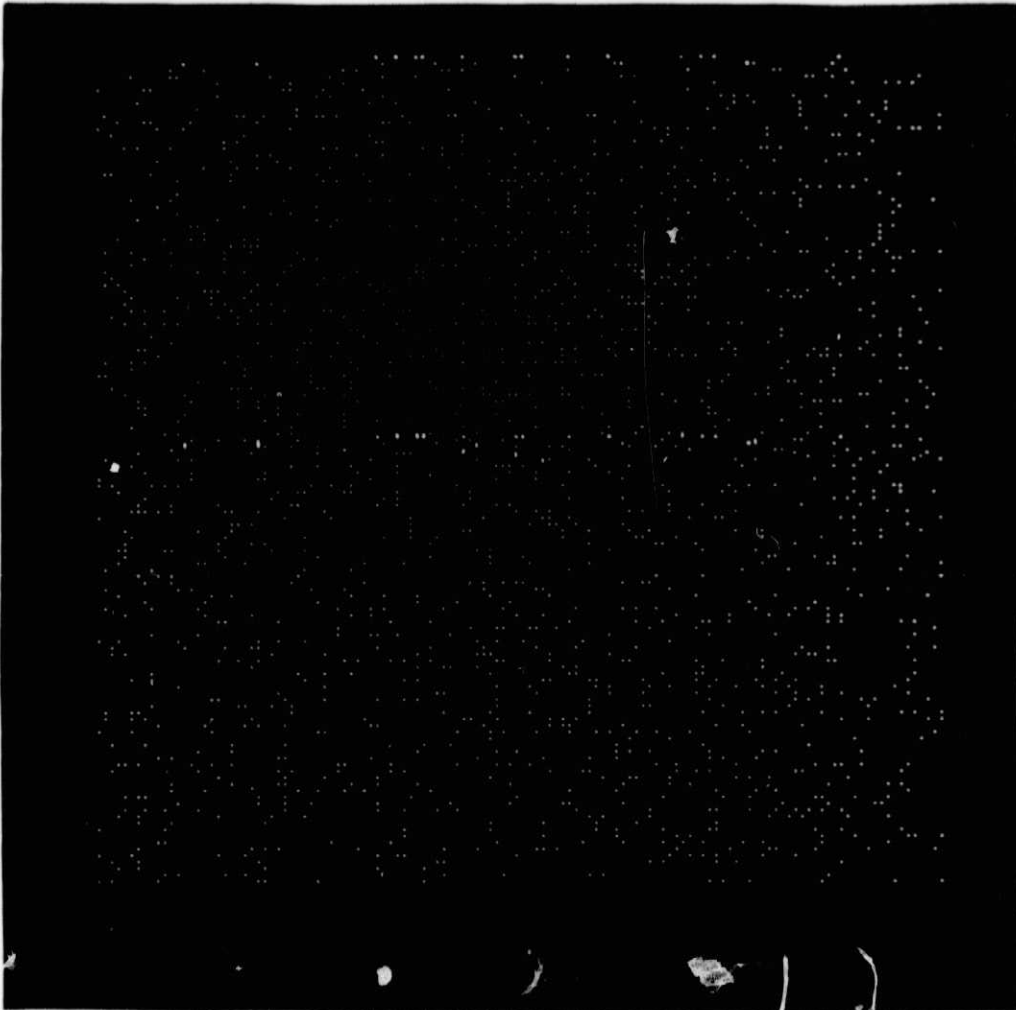


FIGURE 8. TRUTH TABLE FOR 128 x 128 DATA MASK

## SYSTEM CONSIDERATIONS

In this section various aspects of the PRPC will be analysed and discussed with the goal of pointing out some of the important design criteria and assessing the ability of available components and materials to function as required in an operational photorefractive page composer. Among the subjects discussed are the photorefractive material, some optical design considerations, and the availability of detectors which would be compatible with the optimal PRPC design.

The major problem in constructing a PRPC to operate at a data rate of  $10^6$  bits/sec using reasonable laser powers is shown to be the poor sensitivity of available photorefractive materials. This problem can be partially solved by reducing the bit size, but excessive reduction of this dimension will lead to optical problems. It will be shown that the performance of the PRPC is remarkably insensitive to variations in the phase shifts involved, and that the appropriate detector arrays are within the current state of the art.

## PHOTOREFRACTIVE MATERIAL CONSIDERATIONS

### Material Sensitivity

The behavior of the photorefractive material will be described in terms of the following quantities:

$t$  - the thickness of the photorefractive material

$d$  - the diameter of a bit on the PC

$\Delta n$  - the change of index of refraction

$\lambda_H$  - the wavelength used to write the hologram of the page.

The index change corresponding to a phase shift  $\Delta\theta$  is

$$\Delta n = \frac{\lambda_H}{2\pi} \frac{\Delta\theta}{t} \quad (1)$$

We will see below that typical values for the parameter in Equation 1 are  $\lambda_H = .633 \mu$ , and  $t = 1 \text{ mm}$ . Therefore, to achieve the optimal phase shift

of  $\pi$  radians, we require  $\Delta n = 3.2 \times 10^{-4}$ . It is obviously of critical importance to know how much laser energy is required to produce this change. To perform this calculation we will assume that the region in which the  $\Delta n$  occurs is a perfect cylinder of diameter  $d = 50 \mu$  and height  $t = 1 \text{ mm}$  and will explicitly consider a number of photorefractive materials.

LiNbO<sub>3</sub>. For iron doped LiNbO<sub>3</sub>, we have determined<sup>(3)</sup> that irradiation with  $E = 0.15 \times 10^{-2} \text{ joules/mm}^2$  of  $.488 \mu$  radiation leads to a change in index of refraction of  $3.79 \times 10^{-5}$ . Assuming that  $\Delta n$  is linear in  $E$ , we find that approximately  $25 \times 10^{-6}$  joules are required to produce a  $\Delta n$  of  $3.2 \times 10^{-4}$  in the  $50 \mu \times 1 \text{ mm}$  volume.

cis-trans Material. It has been shown<sup>(4)</sup> that cis-trans isomerization of  $\Delta M$  moles of cis-4-nitro-4'-methoxystilbene in solution leads to an index change given by

$$\Delta n = 2.337 \times 10^{-2} \Delta M.$$

To obtain the desired value of  $\Delta n$ , it is therefore necessary to switch

$$\begin{aligned} & \frac{3.2 \times 10^{-4}}{2.337 \times 10^{-2}} \frac{\text{moles}}{\text{liter}} \times 6.02 \times 10^{23} \frac{\text{molecules}}{\text{mole}} \times 1.96 \times 10^{-9} \frac{\text{liter}}{\text{bit}} \\ & = 1.62 \times 10^{13} \frac{\text{molecules}}{\text{bit}} \end{aligned}$$

Assuming half the writing light is absorbed and that the isomerization proceeds with a quantum yield of  $1/2$  we see that  $4 \times 10^{12}$  photons or  $1.6 \times 10^{-6} \text{ J}$  of blue light are required to write a spot.

Unfortunately, the above results apply only to stilbene in solution. Experiments with various molecules in rigid matrices have yielded much lower values<sup>(3)</sup> of  $\Delta n/\text{photon}$  due to decreased quantum yield values. The numbers appropriate to the PRPC are summarized in Table 1 for several molecules.

Goal Memory Material. By "goal memory material" is meant a photorefractive material capable of satisfying the memory plane requirements initially set up for the BORAM system, that is, the ability to form a 1 percent efficient phase hologram with  $50 \mu \text{ joules/mm}^2$  of writing energy. Application of the diffraction efficiency equation,

$$\eta = \sin^2 \left( \frac{\pi \Delta n t}{2\lambda \cos \theta} \right) \quad (2)$$

where  $t$  is the hologram thickness, and  $\theta = 20^\circ$  is the angle between the two writing beams, indicates that such a material would require  $0.56 \mu\text{J/bit}$  if used as a page composer material.

The above results are summarized in Table 1. In addition, the laser power required to write at the rate of  $10^6$  bits/sec is indicated. It can be seen that both the "ideal" stilbene and the goal memory material have sufficient sensitivity to perform well. Of the available materials,  $\text{LiNbO}_3$  lacks about a factor of 25 in sensitivity, some small part of which may be recovered by using wavelengths shorter than  $4880\text{\AA}$ . It is evident that much more work will have to be done on the cis-trans materials before they are sufficiently sensitive to be seriously considered for this application.

TABLE 1. OPTICAL ENERGY AND POWER REQUIREMENTS FOR VARIOUS PHOTOREFRACTIVE MATERIALS IF USED IN PRPC

Material	$\frac{\text{J/mm}^2}{\Delta n}$	$\frac{\text{Joules}}{\text{bit}}$ ( $\Delta n = 3.2 \times 10^{-4}$ )	Watts for $10^6$ bits/sec
$\text{LiNbO}_3:\text{Fe}^*$	39	$25 \times 10^{-6}$	25
cis-trans			
"ideal" cis-trans material	2.5	$1.6 \times 10^{-6}$	1.6
stilbene* in gel	$1.2 \times 10^3$	$7.5 \times 10^{-4}$	750
indigo* in polymer	$6.6 \times 10^5$	0.4	$4 \times 10^5$
"Goal" memory material	0.9	$.56 \times 10^{-7}$	0.56

\* Derived from data in Reference 3. Here we are concerned with incident rather than absorbed energy, so values differ from those tabulated in Reference (3).

### Optimization of Write-Erase Cycle

One of the major advantages of the double exposure hologram technique used in the PRPC is the fact that it is never necessary to completely erase the page composer. Nevertheless, since all materials must show a saturation in their photorefractive behavior, some provision must be made for erasure. Since the details for optimization of the write-erase procedure must depend upon the specific photorefractive mechanism, we will discuss only a representative example based upon the reversible photoconversion of an atomic or molecular species A to species B. For this situation, the change in index as a function of write (erase) energy density is exponential, as shown in Figure 9. The figure also shows erase behavior for a fixed erase intensity applied after various degrees of A  $\rightarrow$  B conversion. We see that A  $\rightarrow$  B conversion process is essentially linear at the A-rich (left) end of the curve, but that the B  $\rightarrow$  A conversion is more efficient at the high end. A compromise must therefore be made between writing linearity and erase efficiency. The details of the compromise will be influenced by the allowable departure from ideal contrast ratio as discussed below.

### OPTICAL CONSIDERATIONS

#### Effect of Phase Shifts Upon Contrast Ratio

The contrast ratio in the reconstruction of the data is dependent primarily on three factors; the hologram intensity ratio, the reference beam phase shift between holograms, and the phase shift produced by writing a bit in the PRPC. The contrast ratio can be calculated by taking the vector sum of the various components of the two holograms used to record the data. Figure 10 shows how the various components are to be added. A is the amplitude of the first (reference) hologram. B is the amplitude of the second hologram in the background and points where zeros are to be recorded. B' is the amplitude of the data points where ones are to be recorded. We will assume there is no photochromism so B' will be

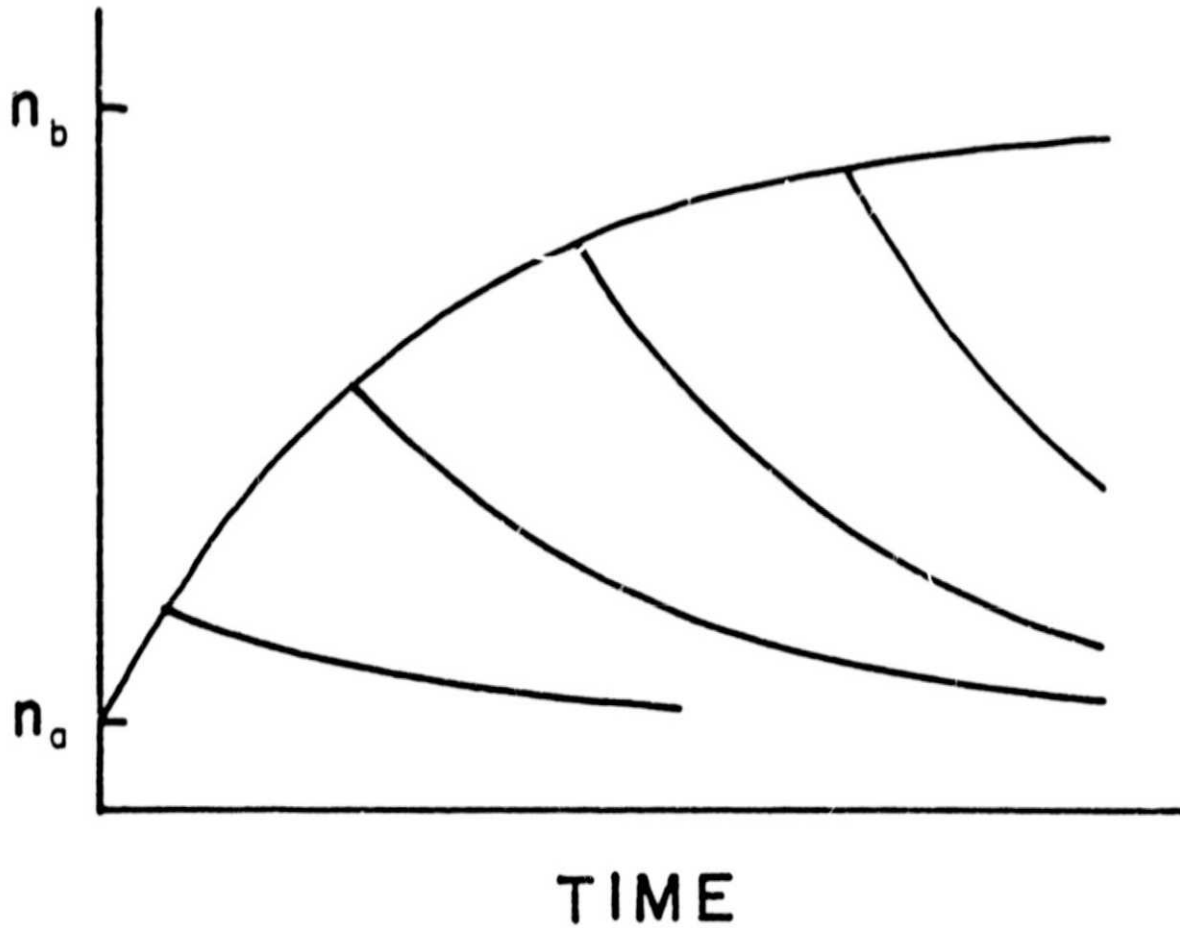


FIGURE 9. TYPICAL BEHAVIOR OF INDEX OF REFRACTION DURING WRITE-ERASE CYCLE. WRITING IS ACCOMPLISHED BY PARTIAL CONVERSION OF A TO B. ERASE BEHAVIOR IS SHOWN FOR APPLICATION OF THE SAME ERASE POWER INITIATED AT SUCCESSIVE POINTS ALONG THE WRITE CURVE. THE WRITING POWER IS, OF COURSE, ASSUMED TO BE TURNED OFF DURING THE ERASE OPERATION.

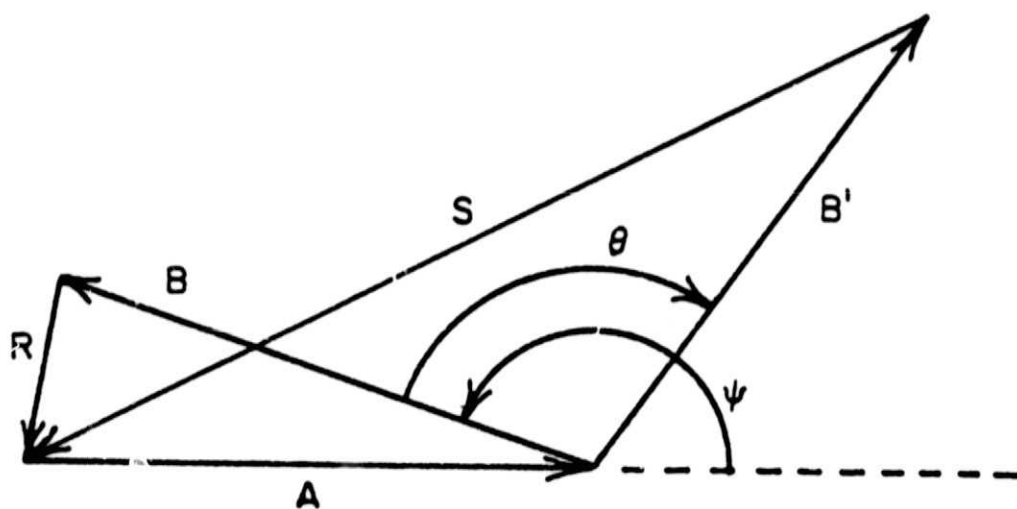


FIGURE 10. DIAGRAM FOR VECTOR ADDITION OF TWO PHASE SHIFTED HOLOGRAMS

equal to B.  $\psi$  is the phase shift introduced in the reference beam between the two hologram exposures.  $\theta$  is the phase change written in the PRPC in the "one" positions. R is the "zero" amplitude and S is the "one" amplitude. K is the intensity ratio of the two holograms. The contrast ratio C, is the intensity ratio of the "ones" to the "zeros".

The background and spot ("one") intensities are given by Equation 3 and Equation 4, respectively.

$$R^2 = A^2 + B^2 + 2AB \cos \psi \quad (3)$$

$$S^2 = A^2 + B^2 + 2AB \cos (\psi - \theta) \quad (4)$$

The contrast ratio is given by

$$C = \frac{S^2}{R^2} = \frac{K + 1 + 2 K^{1/2} \cos (\psi - \theta)}{K + 1 + 2 K^{1/2} \cos \psi} \quad , \quad (5)$$

where

$$K = A^2/B^2 \quad . \quad (6)$$

Figure 11 shows the contrast ratio as a function of  $\psi$  for several values of K and  $\theta$ . As can be seen the contrast ratio is rather insensitive to the phase shift in the PRPC. A phase shift of only  $90^\circ$  instead of the optimum  $180^\circ$  reduces the contrast by only about 50 percent. The contrast ratio is also fairly insensitive to the intensity ratio between the two holograms. A K value of .8 still capable of producing a 160:1 contrast ratio. However, the contrast ratio is quite sensitive to the phase shift  $\psi$  of the reference beam between holograms. As was mentioned before, an error of  $12^\circ$  from the desired  $180^\circ$  reduces the contrast ratio below 100:1.

#### Thickness of the Photorefractive Material

The maximum usable thickness of the photorefractive material for the PRPC is limited by two related problems, overlapping of the spots and decrease of intensity of the writing beam away from the "focal" plane. Both of these problems are due to diffraction phenomena. A usable criterion for both cases is to use the point at which the intensity on the beam axis

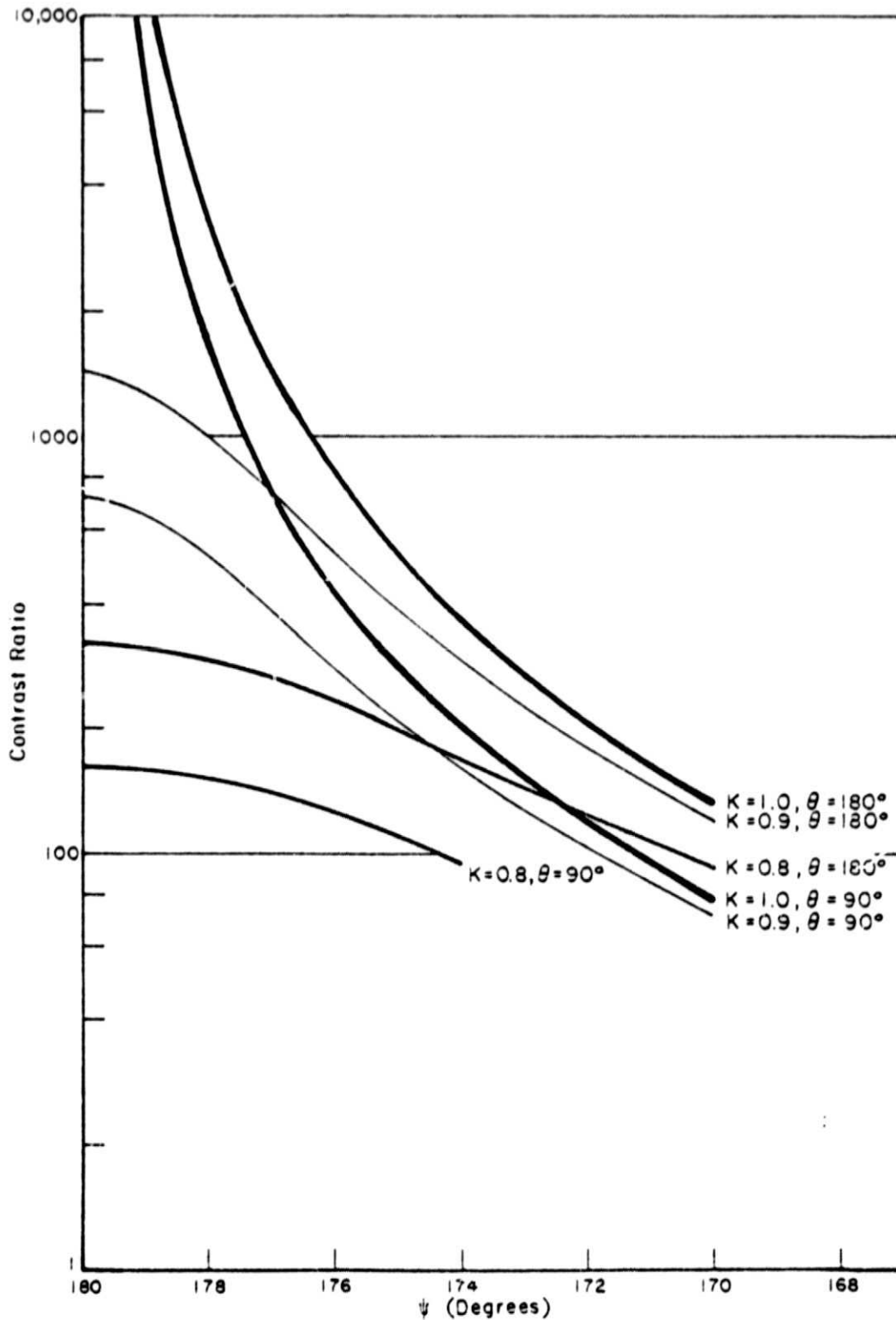


FIGURE 11. CONTRAST RATIOS AS A FUNCTION OF  $\psi$ , THE REFERENCE BEAM PHASE SHIFT, FOR SEVERAL VALUES OF THE HOLOGRAM INTENSITY RATIO  $K$ , AND BIT PHASE SHIFT  $\theta$

falls to 80 percent of its peak intensity as the limit of the usable beam extent. For a beam with a gaussian profile with its waist  $r_0$  at the PRPC its diameter  $r_2$  at a distance  $d_2$  from the waist is given by

$$r_2 = r_0 \left( 1 + \left[ \frac{d_2^2 \lambda}{\pi r_0^2} \right]^2 \right)^{1/2} \quad (7)$$

The on-axis intensity drops to 80 percent of its peak value when  $\frac{r_0^2}{r_2^2} = .8$ . This gives a value of  $\frac{.8 d_2^2 n}{\lambda_{air}}$  for the maximum thickness. Figure 12 is a plot of maximum allowable thickness of the PRPC material versus the spot diameter for two writing wavelengths and two indices of refraction of the material.

The use of small (100  $\mu\text{m}$ ) center to center spacing of the data in the PRPC puts an upper limit of 15-30 mm on the PRPC hologram spacing due to the limited resolution of 1 mm diameter holograms. This then implies a larger angular swing of the hologram writing beams to reach a new hologram location than is required by larger format PC's. This is of course no problem if the hologram plane can be moved.

#### Page Composer Read-Out Efficiency

One of the major problems in the BORAM system is the delivery of enough energy to the holographic memory plane to enable data recording at a rapid rate while using reasonable laser powers. It is therefore important that the page composer have minimal insertion loss and that the hologram writing signal beam be used as efficiently as possible.

One of the major advantages of the PRPC is that it can be constructed using materials which are essentially completely transparent to the radiation used to write the hologram in the memory plane. However, there is still a geometric inefficiency which can be overcome by the optical approach described below. The problem and the suggested solution is not unique to the photorefractive page composer, but should be applicable to a variety of page composer concepts.

The desired form of the data in a page composer is an array dots of diameter  $d$  with an average center to center spacing of  $2d$ . For this geometry, only about 20 percent of the area of the page composer is active.

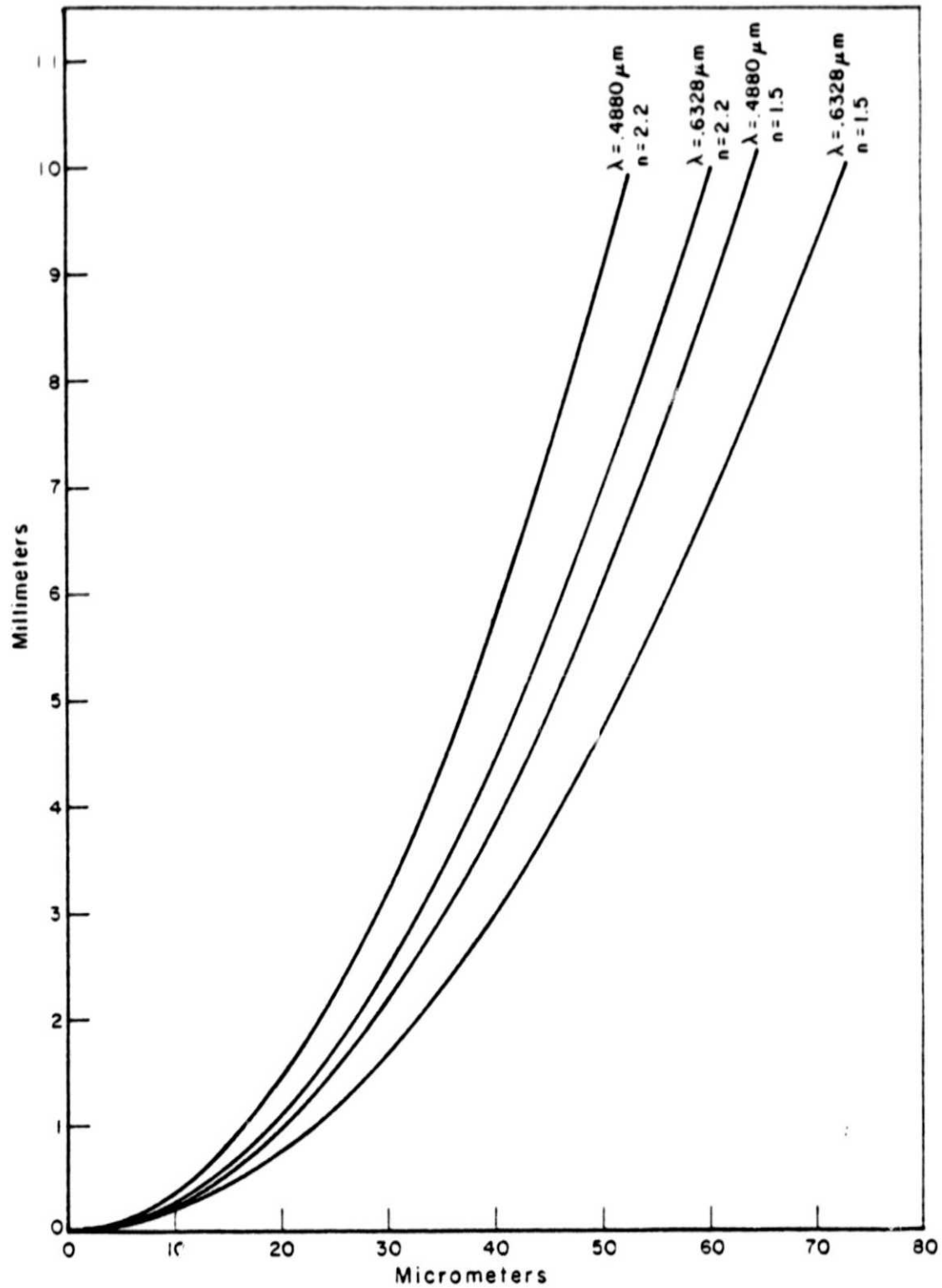


FIGURE 12. MAXIMUM ALLOWABLE PHOTOREFRACTIVE PLANE THICKNESS AS A FUNCTION OF SPOT DIAMETER FOR SEVERAL VALUES OF  $\lambda$  AND  $n$

That is, only 20 percent of the area has useful information; the rest of the area never changes. If the page composer is illuminated by a beam of uniform intensity, this means that at best only 20 percent of the hologram writing light energy carries useful information. It should be possible to take a large fraction of the 80 percent of the light that falls on the inactive regions and put it through the active areas by using a lenticular or holographic lens array. Referring to Figure 4 the lens array would be placed between the dichroic mirror and the Fourier transform lens so that it projects an appropriate array of dots on the photorefractive material. In this way an increase of up to a factor of four in the PC efficiency would be effected and the sensitivity required of the holographic recording material would be reduced proportionately.

#### The Detector Plane

To read out the information stored in the memory, it is necessary to reconstruct the individual holograms onto a detector array which is capable of being read out serially. Since the optics are simplest if the data array on the PRPC is dimensionally the same as the detector array, a brief survey of detector technology was performed to ascertain the availability of suitable detectors.

The detector plane requires a two-dimensional array of light sensing elements which can be sequentially scanned and read out serially line-by-line or column-by-column. The array should be 128 x 128 elements on approximately 100  $\mu\text{m}$  centers, yielding an overall dimension nominally 1.28 x 1.28 cm. The overall dimension can be rectangular rather than square if necessary. The light-sensitive element should be on the order of 50  $\mu\text{m}$  in diameter. Scan rate should be at least  $10^6$  bits/sec. Spectral sensitivity should be in the visible region with maximum response to be determined by the requirements of the holographic recording material.

Several different types of imaging devices have been developed which meet or exceed these requirements (in terms of element density). These range from the conventional TV vidicon and similar electron-beam scanning devices employing a continuous layer of light-sensitive material

for the screen, to the electron-beam-scanned array of discrete detectors, to the electronically or self-scanned array of detectors which, since it does not require an electron beam, operates free of an evacuated enclosure. It may be possible to use an off-the-shelf unit of one or another of these imagers with but minor modification to the scanning circuitry to fit the requirements. In other cases, such as an imager employing a two-dimensional array of detector elements, the array may have to be custom-manufactured by techniques based on proven technology. Following are brief descriptions of different types of imagers which can be adopted to the application of interest.

Silicon self-scanning photodiode arrays, both linear and two-dimensional, are manufactured by the Reticon Corporation. Electronic digital multiplexing is used to sample each element sequentially, or, by appropriate circuit design, in some other preferred order. The photodiode integrates photocurrent during its "off" period and therefore sensitivity is a function of scan rate. A  $32 \times 32$  array, with elements on  $100 \mu\text{m}$  centers, is a stock item.<sup>(5)</sup> Each element has a light-sensitive area of  $195 \mu\text{m}^2$  or  $14 \mu\text{m}$  on edge (if square). The balance of the element area is devoted to the shift register. Peak spectral response is at  $0.95 \mu\text{m}$ . Sampling rates range from  $2 \times 10^4$  to  $5 \times 10^6$  Hz.

CCD (charged-coupled device) self-scanning imaging arrays employ silicon technology for both the detector and associated charge-coupled elements. CCD imagers have the potential for higher element density and lower inherent noise than the photodiode arrays. An analog charge-transfer shift-register scheme is used to sample serially each detector element and move the acquired charge packets through a series of potential wells to the output. Scanning patterns are restricted to sequential scanning, although interlacing of lines, as in TV vidicons, can be provided. The goal of 512-line, TV-quality imaging has been achieved, although imagers of poorer resolution are on the market.

The Fairchild Camera and Instrument Corporation is a principal manufacturer of both linear and two-dimensional CCD arrays. They have announced a  $190 \times 224$ -element array on a  $5.7 \times 4.4 \text{ mm}$  chip.<sup>(6)</sup> Their CCD

201 device is a  $100 \times 100$  element array with interlaced scanning having an aspect ratio of 4:3.<sup>(7)</sup> Elements, which comprise both a photosensitive and a light-shielded charge-storage region of about equal area, are  $30 \times 20 \mu\text{m}$ . Center-to-center spacings are  $40 \times 30 \mu\text{m}$ . The array dimension therefore is approximately  $4 \times 3 \text{ mm}$ . The spectral response maximum occurs at about  $0.95 \mu\text{m}$ . Scan rate is from  $10^5$  to  $4 \times 10^6 \text{ Hz}$ .

Vidicons and related electron-beam scanning-type imaging devices (such as the Plumbicon) have been, for the most part, designed for studio and industrial TV with emphasis on high resolution. Resolution, in most cases, is limited by the diameter of the electron beam rather than the characteristics of the photosensitive screen. Nominal TV vidicon resolution is 20 line pairs per millimeter, or effectively a line center-to-center spacing of  $50 \mu\text{m}$ . Circular photoconductive screen diameters generally are 0.5, 1.0, or 1.5-inch and accommodate an image aspect ratio of 4:3. The spectral response of vidicons peaks at about  $0.45 \mu\text{m}$ , although this can be tailored within the visible region in custom designs. Scan rates can be extended into the several-megahertz region. Moderate alternations to the scanning and focusing circuitry conceivably could adapt a 0.5-inch vidicon to the application of interest.

A number of imaging devices have not been discussed. The CID (charge-injection device) imager developed by the General Electric Company, is similar in the respects of interest to the CCD imager. Sampling is done differently and access is provided to each element independently. Thus, random access or nonsequential scanning is possible. Arrays comparable in performance to the CCD imager, and possibly having lower noise, have been announced but are not offered on the open market. Element density can be expected to be about the same as for the CCD arrays.

A number of electron-beam scanned imaging tubes have been omitted since they differ from the vidicon, as far as performance is concerned, primarily in sensitivity, spectral range, susceptibility to "blooming", etc. These include the image orthicon, image isocon, lead-oxide target and silicon-target tubes, the SEC (secondary electron conduction) tube, the return-beam vidicon, the pyroelectric vidicon, and more. Some of these

have photoemissive rather than photoconductive targets. But as far as "element" size, center-to-center spacing, etc., goes, they are all comparable to the vidicon.

It is evident from this brief review of relevant detector technology, that there is a variety of detectors which are compatible with the geometry of the PRPC. It should therefore be possible to maintain the compact PRPC system and simultaneously have the advantage of the page composer and detector planes being equidimensional.

## SUMMARY AND CONCLUSIONS

During the course of this program, it has been clearly demonstrated, in terms of a laboratory model, that the photorefractive page composer concept is a sound one and that through the use of the double exposure hologram technique, it is possible to construct a  $128 \times 128$  bit array with high contrast using a page composer which is only 1.3 cm on an edge. It has been established that the only significant obstacle to the construction of a brass-board model working at  $10^6$  bits/sec is the lack of sensitivity of the photorefractive materials which were considered during the course of this study. Possible materials for future consideration are the photoplastics. While they have more than the required sensitivity, their stability and suitability for double exposure holography has not been investigated. If the photoplastics, or other suitable materials are available, then the photorefractive page composer could certainly be built to perform in a highly efficient fashion which would result in an overall reduction of the size of the BORAM system and an easing of the requirements upon the sensitivity of the holographic recording material.

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